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System-Level Modeling of Silicon Microphones Including Distributed Effects

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Abstract

We present a hierarchical modeling methodology, which combines short simulation times with the attention to detail as provided by finite element-based techniques. It enables predictive simulation of micro-devices even if exhibiting complex geometries like the MEMS microphone considered in this work. The challenge to properly account for mechanical, electrical and fluidic effects including their respective couplings has been solved by applying a mixed-level approach realized in a commercial system-level simulation environment. This enables to systematically include not only lumped but also distributed effects, like viscous damping and inhomogeneously distributed electrostatic forces. Applying the calibrated and validated model we obtain important microphone characteristics and, moreover, insights into distributed phenomena affecting the device operation. Hence, this constitutes a powerful tool for re-design and optimization as well as for the development of new prototypes.

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Keywords: MEMS; modeling; microphone; system-level models; multiphysics; compact models

1. Introduction and problem description

Silicon microphones provide several advantages compared to conventional solutions such as low costs due to mass production and their fitness for surface mountable and reflow solderable devices. However, increasing demands on their performance require further improvement of microphone characteristics. This implies a profound understanding of all governing effects, which can only be gained by combining physics-based simulation with

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dedicated device characterization. The challenge hereby lies in the accurate and efficient modeling of mechanical, fluidic and electric effects and their interactions, also for complex geometric assemblies like the state-of-the-art silicon microphone investigated here.

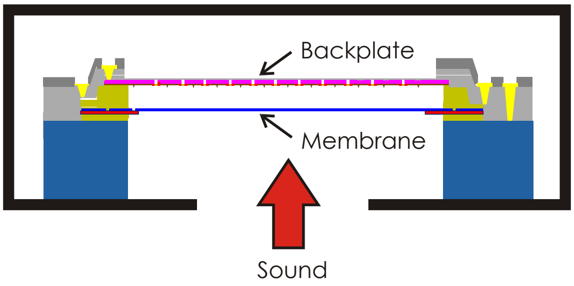

Fig. 1. Schematic view of microphone design. The movable membrane is actuated by pressure variations from incoming sound waves. The oscillations are detected through the capacitance change between the membrane and the perforated backplate.

This silicon microphone, designed and manufactured by [1] and sketched in Fig. 1, is exemplarily used to set up the modeling methodology. It consists of a movable membrane and a static backplate. An incoming acoustic wave excites the membrane to oscillate in vertical direction. The resulting motion of the membrane is detected through the capacitance change of the capacitor formed by membrane and backplate. Damping of the membrane oscillation is reduced by densely perforating the backplate so that the squeezed air inside the gap can easily escape. This minimizes losses and, as a consequence, enhances the signal to noise ratio. The locally varying membrane deflection, electrostatic forces, fringing fields and, even more critical, the accurate description of the air flow through the perforated backplate with its thousands of holes demand for a modeling methodology which provides simulation models suited for an efficient simulation of the overall system performance while, at the same time, including all relevant and even distributed effects of each contributing subsystem in an accurate manner.

2. Modeling methodology

In order to meet the above mentioned requirements, we extended the hierarchical modeling approach derived in [2] to the needs of silicon microphones. This is achieved by following the modeling scheme outlined in Fig. 2.

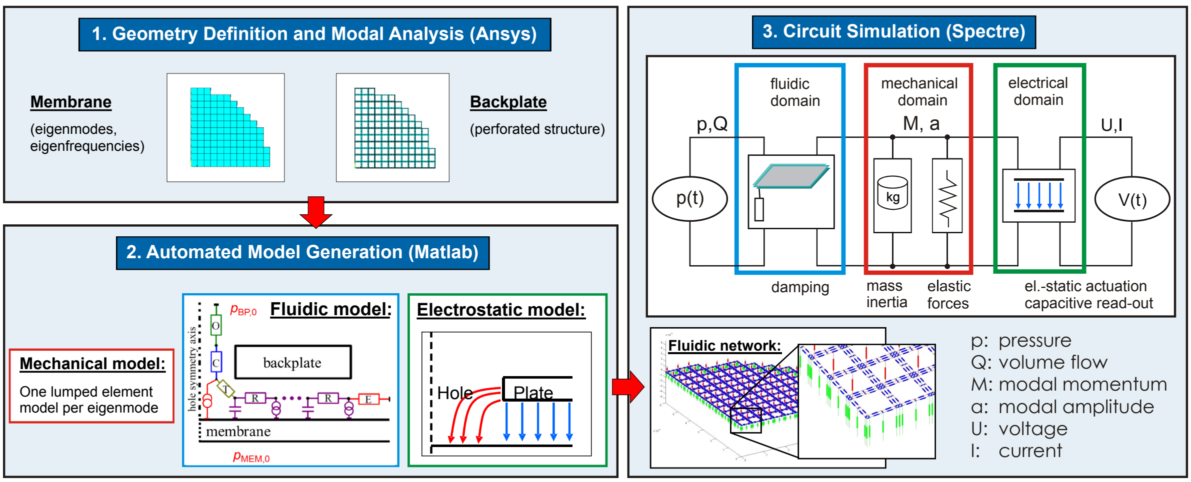

Fig. 2. Applied modeling methodology: First, the geometry of the membrane and backplate is defined and a modal analysis is performed in an FE simulator. Then, physically-based problem-adapted compact models are automatically generated and finally, these models are coupled in a generalized Kirchhoffian network and simulated in a circuit simulator.

In a first step the membrane and backplate geometry is defined and a modal analysis of the membrane is carried out in a finite element (FE) simulator. In the second step the topological information is translated into system-level models for the mechanical, fluidic and electrostatic domain using an automated model generation procedure. The mechanical model constitutes a lumped element model generated by the modal superposition technique in order to describe the membrane-type motion. The fluid flow between membrane and backplate is modeled by a fluidic network discretization of the Reynolds equation combined with fluidic resistances accounting for the flow through the perforation holes (details, see [3]). The local membrane deflection displaces the air inside the gap, thus generating a flow, which results in pressure changes inside the air gap. These pressure changes lead to local damping forces acting on the membrane, which constitutes a bidirectional coupling between fluidic and mechanical model realized by inserting the time-varying modal amplitude of the mechanical model into the Reynolds equation. The electrostatic domain is discretized in an electrical network, which consists of an assembly of differential plate capacitors. Fringing fields occurring at perforation holes are accounted for by adding geometry-dependent correction factors based on [4]. The electrostatic forces again influence the mechanical movement of the membrane and vice versa, which constitutes a bidirectionally coupled phenomenon as well. Finally, in step 3, all sub-models are assembled in a generalized Kirchhoffian network at system-level to form the entire model of the microphone ready for being simulated in a standard circuit simulator. This model now allows for simulation of the overall system performance including all relevant couplings between the involved energy domains while exhibiting still short simulation times of only a few minutes despite of the attention to details originating from the inclusion of distributed effects. All models are physics-based in the sense that they contain all important design parameters and their physical dependencies on ambient and operating conditions in an accurate and transparent manner. Since the varying gap-height is implemented in each sub-model consistently, the model is also suited for large signal applications. As a further benefit all important physical parameters - applied bias voltage, ambient pressure, and initial height of the air gap, just to name a few - can be accessed at system-level. The combination of low simulation times and the accessibility of design parameters qualify the generated models as a powerful tool for design optimization.

3. Model validation and results

The modular and hierarchical character of the presented methodology offers several advantages with respect to flexibility and tailored modeling complexity, but, as a consequence, the increased number of applied sub-models and, therewith, the complexity of the simulation demand for a careful and proper model calibration and validation procedure. To this end, each of the sub-models has to be calibrated and validated separately before they are connected to form the entire system model. E.g., the fluidic sub-model is extensively calibrated and validated combining FE simulations and measurements for dedicated test structures, as described in detail in [3]. The electrostatic sub-model as well as the correction accounting for the fringing fields is validated by detailed electrostatic FE simulations.

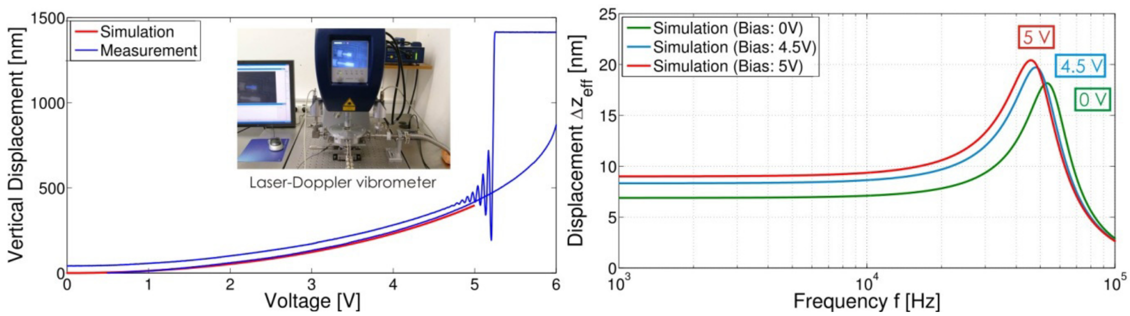

Fig. 3. (a) Model calibration: Exemplarily shown is the membrane deflection due to an applied bias voltage obtained by optical measurements using a laser-Doppler vibrometer to verify the mechanical behavior and the correct modeling of the electrostatic forces. (b) Frequency response of the microphone for various bias voltages. The resonance frequency as well as the sensitivity of the microphone shift with varying bias voltages; both are affected by the non-linear behavior of electrostatic forces (electric spring softening).

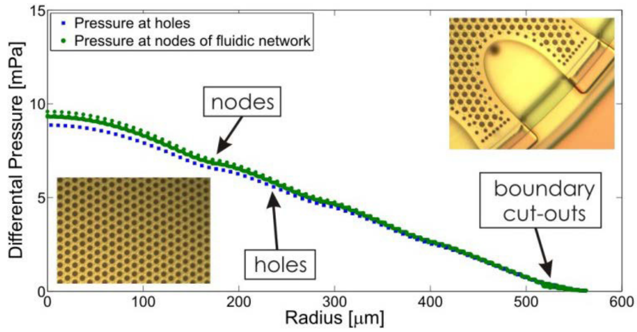

Fig. 4. Pressure distribution inside the gap between membrane and backplate vs. membrane radius. The maximum pressure occurs in the center of the microphone due to the membrane-type oscillation. Cut-outs in the backplate additionally reduce the differential pressure at the boundary.

Unknown model parameters are calibrated by dedicated measurements; in particular, process-induced mechanical stress inside the membrane is extracted from the first mechanical eigenfrequency determined under vacuum conditions by Laser Doppler Vibrometry. The excellent agreement of the vertical membrane displacement over bias voltage, as depicted in Fig. 3(a), is a result of the self-contained calibration of each sub-model. In summary, this extensive calibration and validation procedure supplementing the use of physically based and transparent models, guarantees accurate results and provides the basis for predictive simulation.

Applying the derived modeling scheme important microphone characteristics such as the frequency response can now be investigated as shown in Fig. 3(b). Significant coupling effects as the electrostatic spring softening (change of the effective spring constant induced by the applied electrostatic force) that affect the microphone sensitivity as well as the resonance frequency can be investigated. The accessibility of physical and operational parameters, like the applied bias voltage, enables efficient parameter studies at system-level in order to figure out the potential for optimization of device and system performance. Moreover, the finite network discretization of the fluidic and the electrostatic energy domain allows for studying also distributed effects like the pressure distribution inside the air gap as depicted in Fig. 4, which is affected by the locally varying membrane displacement or perforation density, respectively. These results may again be exploited as valuable input for design optimization with view to viscous loss and, hence, noise reduction.

4. Conclusions

In this work we extended the modeling methodology in [2] to the needs of silicon microphones. Employing the described approach, a tailored, physically based system-level model is derived in an automated procedure for state-of-the-art silicon microphones providing efficient models that describe the overall system behavior as well as deliver detailed insights due to the inclusion of distributed effects. The separate calibration of each sub-model ensures accurate results and, in combination with the use of physically-based transparent models, enables predictive simulations. Furthermore, the modularity of this concept offers the possibility to refine the existing sub-models with view to novel design variants or to extend the existing (sub-)model library with view to additional aspects, like the investigation of packaging effects on the system performance. Thus, this methodology constitutes the basis for fast development cycles and pushes forward the vision of making virtual prototyping a reality.

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